Phase Error Compensation in Fourier Domain for Fast Autofocus of Spotlight SAR

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***Abstract*— In SAR imaging, we propose one of metric-based autofocus techniques. By formulating new metric in Fourier domain, the phase error estimating ability and processing speed are improved at the same time. The proposed method shows strong performance for high frequency phase error.**

Keywords : SAR, Autofocus, PGA, SSA, Sharpness, Metric

I. Introduction

In SAR imaging, un-compensated motions of the aircraft cause phase errors and it degrades the quality of the image. Autofocus process estimates the phase error and eliminates it in the SAR signal history. Many solutions have been proposed. A widely-used technique is phase gradient autofocus (PGA), one of inverse filtering, employs innovative iterative windowing and averaging process [1]. PGA typically produces an accurate approximation of the phase error for low-ordered polynomial errors. However, it has weakness to compensate the high-ordered phase error such like multi-cycle sinusoidal phase error or wideband random phase error. Newly proposed method is metric-based autofocus that estimates phase errors using a particular metric that reflects the focused level of the image and finding the phase error optimizing the metric [2]. The metric for autofocus can be the sharpness or the contrast in the imagery. One of which is stage-by-stage approaching (SSA) that minimizes the entropy of an image [3]. However, SSA is computationally demanding and shows low speed to estimate the phase error. Because it requires many IFFTs to calculate the metric in image domain. Also it sometimes fails to achieve a global optimization. Thus, it is of interest to obtain a fast algorithm while shows a good estimating performance for high-ordered phase error at the same time.

II. Proposed Algorithm Development

Figure 1 shows the autofocus procedure. If we could obtain a metric function in Fourier domain, it is possible to remove the IFFTs process in each iteration of autofocus process and the processing speed would be much faster. So the goal is to obtain metric expression in Fourier domain. Our approach has some assumptions. An image is composed of impulse like points. Blurred SAR image caused by phase error decreases the sharpness of each point. Increasing sharpness makes strong points stronger and weak points weaker. Sharpness maximizing of the image make well-focused image. Such a feature is described with the nonlinear transform and we set up the optimization problem. For given pixel intensity I, we find phase vector ϕ such that

$$\max.\quad f(\phi)=\sum_{n}\sum_{m}\left[I(n,m)\right]^{p}\quad \text{with}\quad p>1 \qquad (1)$$
$$\text{subject to}\quad -\pi\le\phi_o,\phi_1,\cdots,\phi_{M-1}\le\pi$$

The objective function is a function of ϕ but still involves the inverse Fourier transform. The raw data is 1-D Fourier data described in spatial frequency domain only along the azimuth direction. Let consider only one range bin and p equal to two for simplicity. We can use the Fourier relation between the pixel power and the autocorrelation function. The right side of (2) is the where the autocorrelation with lag l. (3) indicates the power theorem and we infer that maximizing each lag of autocorrelation function achieves to maximize the objective function. Next, we apply the feature of autofocus procedure to the objective function in order to simplify the multi-dimensional maximization problem. There is no change of total power during the autofocus procedure because only phase compensation is performed. Therefore, we set the zero lag of autocorrelation as constant while phase compensation is performed given by (4).

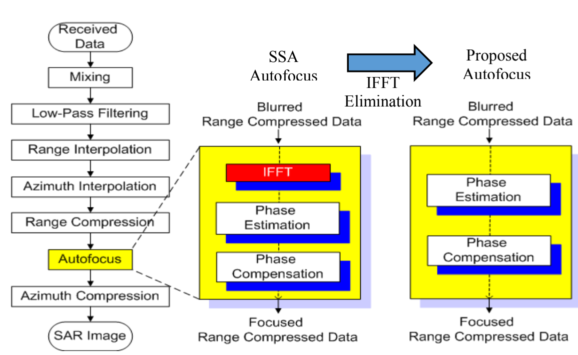
$$I(m)=\left|g(m)\right|^{2}\ \underset{DFT_{k_m}^{-1}}{\overset{DFT_{m}}{\rightleftarrows}}\ R_{GG}[l]=\sum_{k_m}G[k_m]G^{*}[k_m-l] \qquad (2)$$

$$f=\sum_{m}\left|I[m]\right|^{2}=\frac{1}{M}\sum_{l}\left|R_{GG}[l]\right|^{2} \qquad (3)$$

$$R_{GG}[0]=\sum_{k_m}G[k_m]G^{*}[k_m]=\sum_{k_m}\left|G[k_m]\right|^{2} \qquad (4)$$

We note that the phase error is inserted in each column of the raw data identically since we assume that phase errors caused by motion of platform is space-invariant and all the range bins go

Fig. 1. Elimination of IFFT in autofocus procedure



through same phase shift. We exploit the redundancy in the range bins in order to estimate the phase error more correctly. We performed cross-correlation of two different range bins with zero lag. Note that (5) describes the raw range-compressed data in Fourier domain without IFFT. The $n*$ indicates the index of the maximum power range bin. The magnitude vector of this range bin is used as a weighing vector for each column of the range-compressed matrix. After then, weighted summation of the magnitude is conducted for each row. The element of (5) behaviors similar to image pixel value along the range direction by Rayleigh's energy theorem. So, we deals the metric in image domain given by (6). Finally, we find the 1 by M phase error vector that maximizes the contrast function of the image pixel.

$$s(n) = \sum_{m=1}^{M} \left| G(n^*, m) \right| \left| G(n, m) \right| \quad (5)$$

$$f = \sum_{n=1}^{N} s^p(n) \quad \text{with } p > 1 \quad (6)$$

The searching strategy is similar with SSA in that both use the direct descent optimization method. The difference is that the objective function is described in Fourier domain and the maximization is needed in this case. Such a strategy achieves to the maximal sharpness of the image.

III. Simulation Result

Fig. 2 shows the phase error blurring the point target is a mixed version of the low and high ordered phase errors. The simulated scene is a perfectly focused point target as shown in Fig. 2(a). As shown in Fig. 2(b), the point target on the scene center severely distorted by the phase error. The main lobe is corrupted due to the influence of the quadratic component in the phase error and the energy level of the side lobe is increased by the high ordered phase error resulting in loss of contrast in the image. Two large symmetric side-lobe centered on the target in the distorted SAR image, it is caused by the multi-cycle sinusoidal phase error. Wide-band random phase error decreases the contrast by increasing the energy of the side-lobe and makes an effect on the image similar to noise. The PGA result, shown in Fig. 2(c), fails to estimate the high ordered phase error. The side lobe level is still high and two large symmetric side-lobe is still appeared due to the sinusoidal phase error. Fig. 2(d) shows the result of the SSA. The optimizing algorithm is trapped in a local minima and terminated without any iterative operation and the image is still poorly distorted. Fig. 2(e), the image using proposed algorithm, shows the superior compensation performance to the other methods. The main lobe is perfectly focused and the two large symmetric side-lobe that PGA fails to eliminate are eliminated. But the side-lobe level is still high although it shows better than PGA result, because it succeeds to estimate the low ordered and sinusoidal phase error exactly but fails to estimates the wide-band random error clearly. Fig.3 plots the azimuth phase error response corresponding to the results of Fig.2. Also, it is necessary to compare the performance with respect to the algorithm speed. Table I shows the runtime that each algorithm operates for. The runtime itself is not meaningful but we can compare the processing speed of each algorithm with this runtime result since the simulation is performed under the same hardware environment. It is appeared that processing speed of the proposed algorithm is more than 10 times faster than processing speed of the original SSA. This imples that the elimination of IFFT in the metric-based autofocus much improves the processing speed.

Fig. 2. (a) Focused point target image, (b) Blurred image by high ordered phase error, (c) image using PGA, (d) image using SSA, (e) image using the proposed method

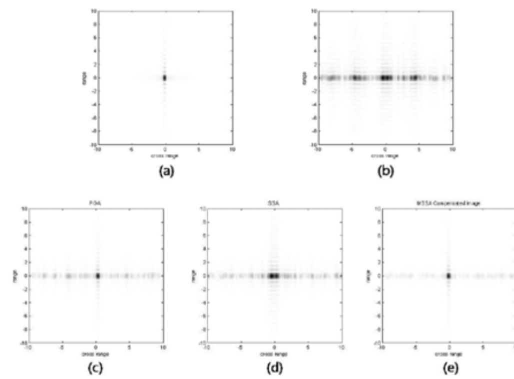


Fig.3. (a) Actual high ordered phase error, (b) Estimation using PGA, (c) Estimation using SSA, (d) Estimation using the proposed method

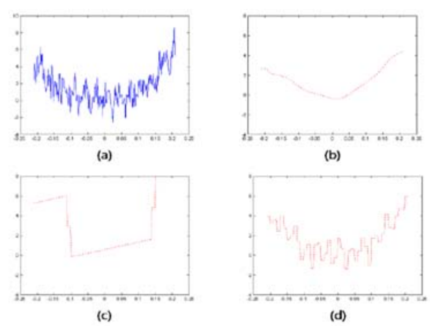


Table I. Comparison of runtime between SSA and the proposed method

Autofocus Method	SSA	Proposed Method
Runtime (s)	170.376	13.440

IV. Conclusion

We propose the metric-based autofocus algorithm that eliminates the IFFTs for fast calculating of the optimal metric while shows strong performance to estimate the high frequency phase error that the conventional method fails to estimate. We demonstrated the autofocusing performance of the proposed algorithm through the simulation result for point target model.

References

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